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FABRICATION AND CHARACTERIZATION OF WOUND CAPACITORS USING AMORPHOUS SILICON DIOXIDE AS THE DIELECTRIC MATERIAL (PREPRINT)

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14. ABSTRACT
Capacitors that perform well at temperatures exceeding 200°C and have energy densities in excess of 5 J/cm³ are an enabling technology for many applications in automotive, geophysical exploration, aerospace, and the military. To address this need Nanohmics has been developing high energy density, temperature-stable film capacitors fabricated using amorphous silicon dioxide as the dielectric material. Fabrication begins with the deposition of ~0.4 µm silicon dioxide films on both sides of a 6-12 µm metalized flexible polymer substrate to form dielectric-coated electrodes. Next, two coated electrodes are wound together into a cylindrical shape to produce a capacitor. Measurements indicate that capacitors fabricated using amorphous silicon dioxide dielectric has stable capacitance, dissipation factor, and breakdown threshold over a wide temperature range. Energy densities in the 5 10 J/cm³ range are theoretically attainable using these materials and fabrication geometries.

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Fabrication and Characterization of Wound Capacitors using Amorphous Silicon Dioxide as the Dielectric Material

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Abstract

Capacitors that perform well at temperatures exceeding 200°C and have energy densities in excess of 5 J/cm^3 *are an enabling technology for many applications in automotive, geophysical exploration, aerospace, and the military. To address this need Nanohmics has been developing high energy density, temperature-stable film capacitors fabricated using amorphous silicon dioxide as the dielectric material. Fabrication begins with the deposition of ~0.4 µm silicon dioxide films on both sides of a 6-12 µm metalized flexible polymer substrate to form dielectric-coated electrodes. Next, two coated electrodes are wound together into a cylindrical shape to produce a capacitor. Measurements indicate that capacitors fabricated using amorphous silicon dioxide dielectric has stable capacitance, dissipation factor, and breakdown threshold over a wide temperature range. Energy densities in the 5-10 J/cm*^{3} *range are theoretically attainable using these materials and fabrication geometries.*

Introduction

One of the most critical components for electronic systems is the capacitor. Even though a capacitor is generally thought of as an inexpensive passive component, its ubiquity in electrical energy storage, filtering, and power conversion, and its tendency to fail catastrophically, emphasize the need for more stable and reliable devices across the electronics spectrum. This is especially true for critical applications and operation at elevated temperatures. The key to producing highly reliable and stable capacitors is through improvements in the capacitor dielectric.

Previous studies have been made on diamond like carbon [1] and oxynitrides [2] to identify alternative dielectrics for fabrication of film capacitors. In this paper we present the results from a study of the use of flexible amorphous silicon dioxide as an alternative dielectric to polymer films in the fabrication of high energy density, non-polar, wound film capacitors. Amorphous silicon dioxide has a higher dielectric constant, better breakdown strength, and is more temperature stable than its polymer counterparts. This allows capacitors fabricated using silicon dioxide as the dielectric to achieve high energy densities with consistent operational properties over a large temperature range and in harsh environments found in many electronic devices. By increasing the breakdown strength and dielectric constant compared to traditional polymer dielectrics, wound film capacitors can be made smaller, thereby reducing the weight and size of many electrical systems. In addition to decreasing the size of wound film capacitors, the temperature stability of amorphous silicon dioxide dielectrics will make capacitors made from this material compatible with the next generation of high temperature / high power electronic devices made using GaN and SiC.

Experimental

In earlier work, we examined a number of dielectric materials in an effort to develop an oxide based film capacitor.[3] Of the oxide dielectrics examined in this study, amorphous silicon dioxide combined the best breakdown strength, good dielectric constant and ease of manufacture. Figure 1 shows the breakdown voltage of a ~0.8 μm thick silicon dioxide film that was reactively sputter deposited on a metalized glass substrate for testing. The breakdown measurement was made by touching the probe tip to the surface of the dielectric and measuring the leakage current as a function of voltage.

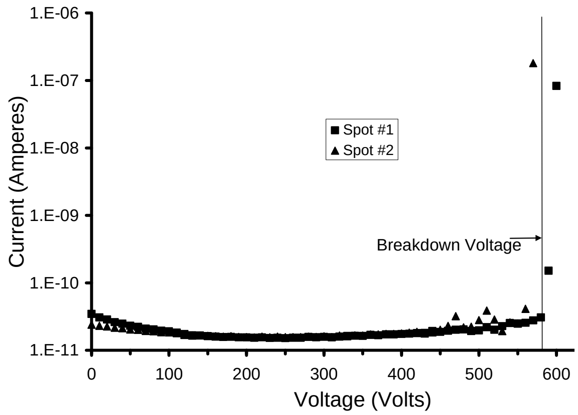


Figure 1. Current vs voltage measurement of ~0.8 μm silicon dioxide film showing the breakdown voltage of the dielectric.

Thermal testing of dielectric films

Capacitance measurements were made using the silicon dioxide films as a function of temperature to examine the temperature stability of the dielectric films. This measurement was made by placing two SiO_2 coated metalized kapton films on top of each other to form a ~1"x1" capacitor. The capacitance was then measured as a function of temperature using a HP 4274 LCR meter operating at 1 KHz. Figure 2 shows the capacitance and dissipation factor of this structure as a function of temperature. In this measurement the dissipation factor increases as a function of temperature while the capacitance remains constant up to the maximum temperature of the heater.

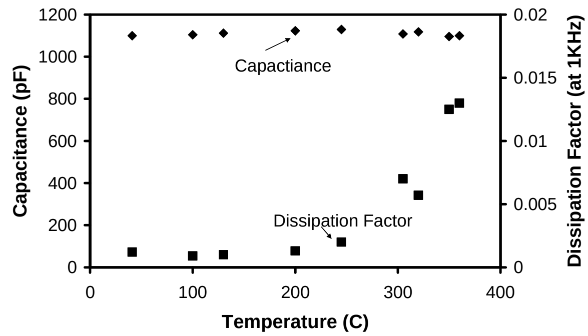


Figure 2. Plot of the measured capacitance and dissipation factor of SiO_2 dielectric on metalized kapton as a function of temperatures.

Rolled Capacitor Fabrication

To make higher value capacitors two SiO_2 coated metalized polymer films are stacked with a slight offset and then rolled together into a cylindrical shape. To insure that the dielectric is not damaged during the rolling process we first studied the flexibility/bendability of the component polymer / SiO_2 structure. This was done by taking a strip of the flexible metalized polymer substrate coated with a 0.7 micron thick amorphous SiO_2 film on each side of the substrate and wrapping it around mandrels of different diameters ranging from 1/2" to 1/8", then unwinding and inspecting the dielectric film. Optical and SEM examination of the material after unrolling showed that the SiO_2 film is continuous and shows no cracking or other defects until the mandrel diameter was smaller than ~3/16". Samples wound around the 1/8" mandrel showed cracking when unwound and inspected. The cracking was primarily on the outside of the films indicating that tensile stress was excessive during winding onto such a small diameter mandrel. Figure 3 shows an SEM micrograph of a SiO_2 coated metalized film wrapped around a 3/8" mandrel.

To fabricate the wound film capacitors, a thin (2 to 9 micron) polymer web with a metal coating on both sides is used as the starting electrode. Next. a thin (<1 μm) layer of SiO_2 is sputter deposited on both sides of the electrode using a custom build web coater. The thin metal coated polymer film serves as a flexible electrode that maintains the clearing properties of traditional wound capacitors. To assemble the capacitor, two such coated electrodes are placed together, slightly offset, and wound into a cylinder. Using this method the capacitance of the device is determined by the

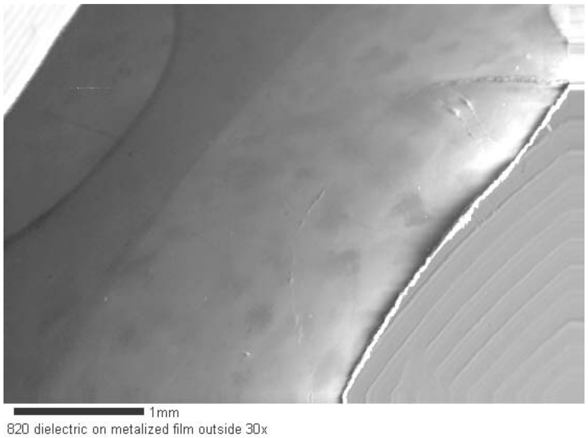


Figure 3. SEM micrograph of a SiO_2 coated metalized polymer substrate wrapped around a 3/8” mandrel. The SEM showed that no cracking of the film occurred during winding.

thickness and dielectric constant of the deposited SiO_2. The metalized polymer web serves as a support structure for the electrodes and should be as thin as possible to maximize energy density. Figure 4 shows the web coating system used to produce the SiO_2 coated electrodes and Figure 5 shows capacitors wound from this film at Dearborn Electronics.

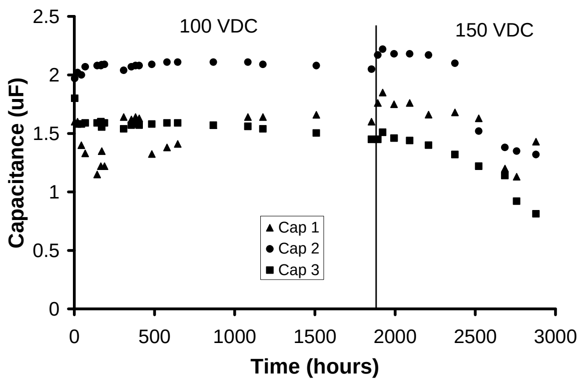
Figure 4. Picture of the custom built web coating system.

Figure 5. Picture of pre-packaged capacitor cores after winding the SiO_2 coated metalized polyester electrodes.

Capacitor testing and discussion

The initial test capacitors were made using ~0.3µm of SiO_2 sputter deposited on each side of a metalized polyester film. Unfortunately problems with the polyester substrate shrinking at temperatures above 70°C caused the SiO_2 dielectric to crack when the capacitor cores were processed through end spray during the packaging process. Preliminary test data were obtained using conductive epoxy as the end electrical contacts. Figure 6 shows the capacitance and leakage current of the test capacitors as a function of time with a continuous DC bias voltage. The capacitors operated and cleared well up to 100 VDC. Failures began to occur when the voltage was increased to 150 VDC after 1800 hours of testing at 100 VDC.

As noted earlier, the initial test capacitors used metalized polyester for the internal electrodes. This choice of polymer proved to be the biggest issue in fabricating a high performance, high temperature capacitor. The polyester shrinks considerably (>1%) at temperatures above 70°C which causes the SiO_2 dielectric to crack and fail at these temperatures. To eliminate this problem we have switched to a 12 micron thick metalized polyimide substrate instead of metalized polyester.



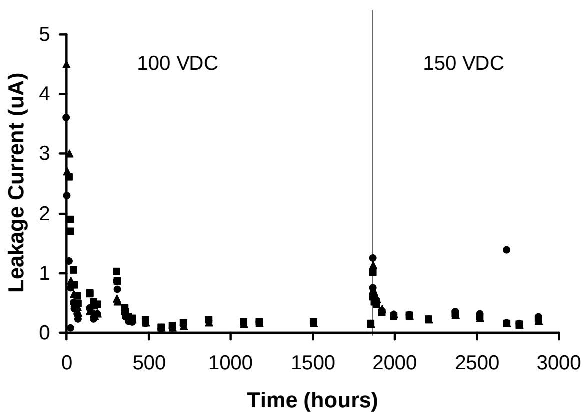


Figure 6. Capacitance(top) and leakage current(bottom) of three test capacitors as function of time. The capacitors operated well up to 100 VDC but began to fail at 150 VDC.

To demonstrate the improved performance with polyimide based internal electrodes, we fabricated six 1.2 μF wound film capacitors at Dearborn Electronics comprising 0.4 μm of SiO_2 deposited on both sides of the metalized polyimide substrate. Three of the capacitors went through standard packaging procedure including electrode end-spray and standard soldering to attach leads. Another three capacitors were assembled using conductive epoxy as the end contact and to attach the leads to the ends of the capacitor. Comparison of the capacitor performance indicated that all capacitors survived the standard packaging process and performed as well or better than the capacitors fabricated using conductive epoxy.

After packaging the fabricated capacitors were subjected to a 70°C vacuum drying process then thermal cycling to 85°C. Burn-in data to date is given in Table I and indicates that the capacitor characteristics are stable. Further testing at higher temperatures as well as fabrication of additional capacitors is ongoing.

Table I. Capacitance and Dissipation factor (DF) of initial 3 test capacitors during vacuum dry and burn in. All measurements were made at 25°C.

	Capacitor 1			Capacitor 2			Capacitor 3		
Vacuum dry	Cap (uF)	IR (meg)	DF (%)	Cap (uF)	IR (Meg)	DF (%)	Cap (uF)	IR (Meg)	DF (%)
Initial	1.20	4.5	2.7	1.56	0.1	9.4	0.42	0.8	8.3
15 h at 25C	1.17	0.5	2.4	1.52	0.03	9.4	0.42	40	8.3
24 h at 70C	1.16	6	2.5	1.51	0.29	9.5	0.40	10000	8.2
72 h at 70C	1.16	50	2.5	1.50	0.29	9.5	0.40	12500	8.3
Burn In									
72 h 85C 30V	1.16	40000	2.8	1.50	27	9.5	0.40	20000	8.3
36 h 85C 50V	1.17	25	2.9	1.50	10000	9.6	0.40	5556	8.4

Conclusions

Silicon dioxide shows promise as a dielectric material for fabrication of high energy density, temperature stable wound film capacitors. Tests on small 1"x1" capacitors made using silicon dioxide dielectric show stable capacitance up to the maximum temperature measured (350°C). Tests of wound capacitors have begun with good initial performance using a metalized polyimide as the internal electrode substrate.

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